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ARMY AVIONICS RESEARCH AND DEVELOPMENT ACTIVITY FORT--ETC F/G 17/7
ARMY GPS-DOPPLER HYBRID NAVIGATION SYSTEM.(U)
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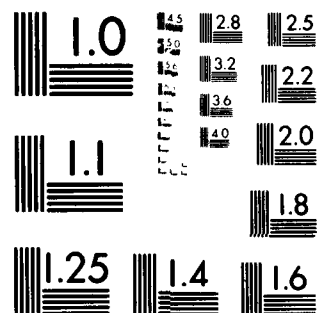
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Army GPS-Doppler Hybrid Navigation System

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JUN 1980

US Army Avionics Research and
Development Activity
Fort Monmouth, N.J. 07703

Introduction - In accordance with the Department of the Army's approved Positioning and Navigation System (PANS) Materiel Need, the Army's stated objective is to field "a mix of externally referenced Positioning Subsystems, self-contained subsystems, and hybrid systems to allow for determination of heading, azimuth, and range for navigation and present position". The intent is to avoid losing completely Pos/Nav/orientation capability for critical missions through dependence by the Army upon any one Nav system in the field. More specifically, the fiscal 1980 Scientific and Technical Objectives Guide defines the need to provide superior accuracy and reliable navigation continuity over the battlefield under all visibility, terrain, and weather conditions for such missions as Aerial Scout Helicopter and Advanced Attack Helicopter. To satisfy these requirements, the Army is developing a family of advanced externally referenced and self-contained Pos/Nav systems and the techniques to hybrid these to satisfy mission requirements at lowest cost.

One of these, the Doppler navigator or, ASN-128, is a fully self-contained, EW Secure, sophisticated, dead-reckoning system. However due to residual heading/attitude and velocity errors, its position accuracy degrades as a function of distance traveled. Therefore, mission aircraft which require high accuracy at all times must use a form of position-updated doppler navigator. ←

The externally-referenced (Satellite-Based) Global Positioning System (GPS) provides high-accuracy, world-wide, position-fixing on a common coordinate system that can be used by all Army elements (ground, air,

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and marine) so that these units can locate themselves and coordinate tactics effectively. However, GPS User Equipment, as a stand-alone navigation system in a tactical environment, is susceptible to intentional and unintentional electronic jamming and/or interference and to terrain, forest, and buildings masking or attenuating satellite signals. GPS also depends on a fully-functioning, satellite constellation complex. Therefore, mission aircraft which require Pos/Nav continuity (as well as accuracy) on the battlefield require some type of augmentation for GPS.

Since the Doppler is effectively invulnerable to jamming in low-flying aircraft (because its highly directional, narrow-beam antenna will reject all signals not radiated from the small area directly below the aircraft), a hybrid of the GPS and Doppler Navigator can efficiently complement each other to satisfy the requirement of the PANS MN and of the STOG for the critical, continuous Pos/Nav of attack and surveillance aircraft. If the GPS is jammed, the Doppler system is still available and can help the GPS re-acquire its satellites. When the GPS is operative, it continuously keeps the Doppler system initialized to a high position accuracy.

PROGRAM INITIATION - Based on these considerations, an exploratory development program was established to derive the parameters that must be incorporated in a GPS/Doppler Hybrid and to assess feasibility experimentally. Prior to analyzing the GPS/Doppler Hybrid Navigation System, a brief description of each individual system is warranted.

NAVSTAR SYSTEM DESCRIPTION - NAVSTAR GPS is a space-based radio position-fixing and navigation system that has the potential for providing, on a global basis, highly accurate three-dimensional position, velocity, and system time to users equipped with suitable (passive) receivers. As illustrated in Figure 1 NAVSTAR GPS consists of three major segments; namely, the space system, the control system, and the user system. These are briefly discussed below.

- Space System - It is planned that the operational space segment will consist of three equi-spaced planes of satellites in circular, 12-hour (~10,000 nmi) orbits inclined approximately 63 degrees to each other. Each orbital plane is to contain eight suitably phased satellites, for a total of 24. Each satellite will transmit a composite waveform consisting of a Protected (P) Signal and a Clear/Acquisition (C/A) Signal in phase quadrature. The P Signal will be used by the "precision" military user and is being designed to resist jamming, spoofing, and multipath and also be deniable to unauthorized users by employing transmission security (TRANSEC) devices. The C/A

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Signal will serve as an aid to the acquisition of the P Signal, and will also provide an uncoded (clear) navigation signal to both the military and civil user.

Both the P and C/A Signals are Pseudo-Noise Biphase Shift Keyed (PN/BPSK) continuous sinusoidal carriers, and both signals carry system data. System data will consist of such information as satellite ephemeris, ionospheric propagation corrections, and satellite clock biases. Each space vehicle will be assigned a unique set of pseudo-noise codes of seven days length for a P signal and one msec length for the C/A signal.

The navigation signals are transmitted on two channels; L_1 and L_2 . Channel L_1 , the Primary Navigation Channel will be 1575.4 MHz and carry the P and C/A Signal, but not simultaneously. System data will always be carried on both channels. The additional L_2 signal will permit the high accuracy user to more accurately determine the ionospheric group delay.

The signal waveform is specifically designed to allow system time to be conveniently and directly extracted in terms of standard units of days, hours, minutes, and integer multiples and submultiples of the second.

- Control System - Four widely separated Ground Monitor Stations will passively measure range and velocity time histories of all satellites in view. This information will be processed at the Master Control Station (possibly collated with a Monitor Station) to use in determining satellite ephemerises, clock drifts, electronic delays, etc.. An upload station located in CONUS will transmit the necessary system data corrections via a secure link to the satellites.

- User System - The user equipment consists of a receiver, antenna, data processor, and control and display unit. The receiver will process the signals from four suitably chosen satellites and will measure four independent pseudo-ranges and pseudo-range rates. The processor will then convert these eight independent measurements into three-dimensional position and velocity of the user, and phase and frequency corrections for the user's clock. The process of solving for position is to be carried out in an earth referenced coordinate frame, which would then be converted for display to geographic coordinates (Lat., Long.), UTM grid coordinates, or any other earth grid convenient for the user. The user equipment will also have the capability of accepting waypoint or destination coordinates in the geographic or UTM grids and providing the user with range, bearing, and cross-track error to any of these points.

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Velocity accuracy characteristics of the fully developed system are:

Horizontal velocity accuracy referred to Lat/Long. = 0.1 knots (RMS)

Vertical velocity accuracy referred to Center of Earth = 0.15 knots (RMS)

Position accuracy characteristics of the fully developed system are:

Horizontal position accuracy = 9 meters (RMS)

Vertical position accuracy = 14 meters (RMS)

AN/ASN-128 Doppler Navigation System Description - The AN/ASN-128 Doppler Navigation System is the Army's Standard Airborne Doppler Navigation Set and consists of a Receiver Transmitter Antenna (RTA), Signal Data Connector (SDC), and Computer Display Unit (CDU). Separately input Heading Reference and Attitude Reference are required.

The RTA and SDC constitute the Doppler Radar Velocity Sensor (DRVS) which continuously measures the velocity of the aircraft. The CDU provides control and display functions for the operator and contains the navigation computer. With inputs from external heading and vertical references, the ASN-128 provides accurate aircraft velocity and present position from ground level to altitudes well above 10,000 feet. It is completely self-contained and requires no ground-based aids.

The DRVS determines the three components of aircraft axis-referenced velocity from measurements of the Doppler frequency shift in radar energy transmitted toward and received back from the ground. As soon as prime power is applied to the DRVS, it transmits microwave energy towards the ground in four non-coplanar beams (See Figure 1) and measures the Doppler frequency shift in the back-scattered energy.

The four Doppler frequency shifts (in terms of components along the beam directions) are then sent to the computer. Using these inputs, together with pitch and roll, the CDU computes the three orthogonal components of velocity in aircraft axis-referenced coordinates. Aircraft velocity is then transformed through true heading to give velocities in north and east coordinates which are integrated to obtain changes in present position.

Velocity accuracy characteristics of the system are as follows:

Horizontal velocity accuracy (RMS) = $.25\% V_t + .1$ knots

Vertical velocity accuracy (RMS) = $.15\% V_t + .1$ knots

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where V_t = Vehicle's true velocity

Position CEP (for distances of not less than 10 nautical miles) shall not exceed 2 percent when inputs of attitude and heading meet the limits and accuracy of,

ROLL (RMS) accuracy = 3° , ROLL Limits = $\pm 45^\circ$

PITCH (RMS) accuracy = 3° , PITCH Limits = $\pm 30^\circ$

HEADING (RMS) accuracy = 1°
(MAGNETIC)

Project Plan - The basic approach for evaluating the effectiveness of a system like the GPS/Doppler Navigator must be empirical rather than analytical. The analytical approach is based on the construction of a mathematical model that includes prediction of system characteristics within the constraints imposed by the analyst. Whatever assumptions were made must be tested; predictions must be verified. Therefore, the empirical approach, collecting data and evaluating system effectiveness by observing performance characteristics in the field, must be the primary method.

In analyzing the GPS/Doppler Hybrid Navigation System, there was a wealth of data to show the performance of stand-alone Doppler and GPS navigation systems. Figure 2 shows the results of over-land navigation accuracy tests performed by the Doppler navigator indicating a Circular Probable Error (CEP) for radial position ranges from 1.3 to 2.0 percent of distance traveled.¹ Field test reports concerning GPS position accuracy indicate a Circular Probable Error (CEP) of 12 meters.² Therefore, by using the improved navigation accuracy of GPS in combination with the Doppler Navigator, direct position updating of the Doppler system can be provided within the accuracy of the GPS.

¹ Research and Development Tech Report, ECOM 4512, Flight Evaluation of the Lightweight Doppler Navigation System, AN/ASN-128 (XE-1) Stanley J. Sokolowski, Avionics Lab., July 1977.

² Final User Field Test Report for the Navstar Global Positioning System, Phase I - Major Field Test Objective Report on navigation accuracy: position accuracy: General Dynamics, GPS-GD-025-C-US-7708, 25 June 1979.

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Although this is not an optimized approach, it will demonstrate the actual performance gained by augmenting a fielded Doppler system with the currently developed GPS and provide valuable information for the next stage of hybrid development. There will be no filtering or data-smoothing in this first approach to integrating the GPS and Doppler system; in effect, the Doppler System is disregarded at the time of the update and the GPS is assumed to "know" the true position and velocity. Since hybrid system position will be referred throughout to known ground bench marks, the error contribution of both GPS and Doppler navigation to the hybrid will be derived.

The next step, based upon the results of the preceding tests, will be to apply Kalman or least squares filtering which will not only update position but extract system error growth rates. At this stage, the manner in which position/velocity/heading error propagates in the system will be known, and by properly modeling how each error propagates, it will be possible to attribute, after several position/velocity/heading fixes, proper proportions of the total position/velocity/heading error to each modeled error source. If the chosen models are correct, the position/velocity/heading error histories should converge, with time, to very small values. The final value they converge to is a function of the error noise amplitude and frequency content in the Doppler and GPS.

Empirical data for an actual GPS/Doppler Hybrid Navigation system is required, therefore, to verify the expected system performance and to provide a baseline. In order to obtain this data, a Texas Instruments GPS High Dynamics User Equipment was integrated with the AN/ASN-128 Doppler Navigator set through a common ROLM 1650 minicomputer, and tests were run in a mobile van in the Fort Monmouth, N.J. area. Figure 3 shows the GPS/Doppler Hybrid system which was installed in the mobile van.

The GPS user equipment consisted of the following:

Antenna/Preamplifier Assembly - Can receive RF signals from up to five satellites; filters, amplifies, and transmits the signals to the receiver/processor assembly.

Receiver - Consists of five single channel receivers connected to a matrix switch output, and a check module for system timing. Acquires, tracks, demodulates, and performs necessary processing to derive pseudo-range, pseudo-range rate, down-link data and system time from the satellite signals.

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Processor - Provides overall GPS Subsystem control and performs navigation calculations.

Instrumentation Interface Unit - Provides intercommunications between the receiver/processor and data acquisition computer. This unit also loads the navigation programs into processor memory.

Control/Display Unit - Provides the human interface and operating mode control functions for overall receiver operation. The unit consists of a multifunction keyboard for receiver mode and navigation display control and alpha-numeric displays for monitoring of navigation parameters.

The Army's AN/ASN-128 Doppler Navigation System operates in conjunction with the Army's Standard AN/ASN-43 Heading Reference Set and MD-1 Attitude Reference Set. The ASN-128 Doppler Radar Navigation Set consists of the following:

Receiver-Transmitter Antenna (RTA) - Transmits RF energy toward the ground in four non-coplanar beams; measures the four Doppler frequency shifts (in terms of components along the beam directions) to the SDC.

Signal Data Converter (SDC) - Accepts heading and vertical reference synchro signals and, along with Doppler beam velocities, transmits serial digital output to the CDU computer.

Computer/Display Unit (CDU) - Accepts from the SDC beam velocities, Heading, Roll and Pitch; performs the Navigation Computations; provides intercommunications between the DRVS and Data Acquisition Equipments.

The Hybrid Navigation Computer consists of:

ROLM 1650 Minicomputer with 32K Core Memory.

GPS/Hybrid Computer Interface.

AN/ASN-128 Doppler Navigator ARINC/Hybrid Computer Interface.

Finally, the Data Acquisition system consists of:

Data Acquisition Computer - Provides overall data acquisition control and the interfaces between the GPS/Doppler and Data Acquisition Subsystems.

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Magnetic Tape Unit - Records system test data/parameters and loads data acquisition software programs into the Data Acquisition Computer.

Teletype Unit - Provides for operator control of Data Acquisition Subsystem and, at operators option, types out all or portions of the system test data/parameters.

Van testing of the GPS/Doppler system not only provides a formidable dynamic environment to ascertain the system's performance, but also is extremely cost effective in comparison to flight tests. The van tests effectively simulate the environment that would be present were the system undergoing a nap-of-the-earth (NOE) flying scenario. Whereas NOE flight involves flight as close to the earth's surface as vegetation or obstacles permit (while generally following the contours of the earth), van tests are, in effect, "flight" on the earth's surface.

As a preliminary to the van testing, a set of detailed 1:24,000 U.S. Geological Survey map for the New Jersey area were used in deriving the latitude/longitude and Universal Transverse Mercator Grid points of easily identifiable landmarks (bridge, intersections, etc.). "Closed loop" navigation courses were selected for these van tests. Checkpoints were chosen such that the landmarks were at least 10 nautical miles apart. During actual van testing, the GPS/Doppler position was recorded as each landmark was passed. Each van run lasted no more than two hours due to the limited GPS satellite constellation visibility over New Jersey. Following each test run, the recorded GPS/Doppler data was reduced, and radial position errors obtained. After the first few runs in the van, it was discovered that GPS positioning data (measured against local bench-mark coordinates) recorded radial position errors ranging from 1 meter to over 200 meters. No particular bias was evident, and re-check of the GPS User equipment in the van along with the Data recording equipment verified these were operating properly. Check with SAMSO revealed one of the satellites had a significant clock malfunction, and another had a clock that was variably questionable.

Additional runs in the van were then made, but, since a maximum of only three satellites could be counted on, local bench-mark altitude was inserted in our GPS User Equipment to overcome the unavailability of the fourth satellite's signals -- and thus allow the GPS set to calculate its best horizontal position. Radial positioning errors were still recorded in a range up to 450 meters. Our GPS set and data recording system were re-re-checked and found operating well. However, further discussions with SAMSO indicated that satellite

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drift rates varied also during the time of their transit from the point of ground up-date in the Western United States to the Fort Monmouth area. Also variable was the time elapsed between any satellite's up-date and its observation on the ground at Fort Monmouth:- thus, when the constellation of three useful satellites is over the Fort Monmouth area, one may have been up-dated only 2 hours ago, but another may have been up-dated as much as 4 hours prior to the time of observation.

Still another factor found to influence the GPS Satellite Signal's positioning accuracy is the angular relation of the satellites with respect to the ground observation point. This relationship, referred to as Geometric Dilution of Positioning (GDOP), varies from orbital swing to orbital swing and, aside from the clock situation, itself significantly influences radial position error. With a full schedule of satellites aloft (24), the GDOP factor may be minimized through the ability of a ground receiver to have access to a constellation with a favorable GDOP. But, with only three working satellites, GDOP variation has full impact on positioning capability.

This situation regarding satellite data transmittal to the GPS User Equipment in our van at Fort Monmouth has significantly delayed the rate at which data could be cumulated for this project and has, therefore, prevented the incorporation in this paper of data and results from a set of satisfactorily completed runs. The recent launching of a new GPS satellite containing four re-designed clocks should improve GPS navigation performance and permit more rapid GPS/Doppler hybrid system testing, data collection, and processing.

SYNERGISTIC BENEFIT - In the course of executing the basic project plan to assemble, test, and evaluate GPS/Doppler Navigation Hybrid Techniques aimed at continuous, accurate positioning over the battlefield, an unexpected synergistic bonus was discovered. This bonus was in the form of an idea that occurred that, in addition to improved positioning, the independently measured GPS and Doppler velocity vectors could be used to derive vehicle heading and attitude as well.

GPS/Doppler Hybrid Velocity Heading Reference - It is well known that the overall navigation accuracy of a Doppler Navigation System is limited by the accuracy of the associated heading reference. In fact, with the high accuracy velocity characteristic of the new Army Doppler, the heading reference has become the major contributor of Doppler navigation error.

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Two classes of heading references are used: magnetic and inertial. The former sensor is subject to errors due to variations in the earth's magnetic field, especially in the polar regions, as well as local distortions of the magnetic field where it is installed. The latter sensor, since it employs a gyrocompass to maintain alignment, is subject to drift error.

In attempting to deal with the heading error source of the Doppler Navigator, it was suddenly realized that, by the addition of the GPS system to the Doppler Navigator, a totally unexpected capability was realized. By judiciously combining GPS and Doppler velocities, a true heading reference system can be generated.³ The coordinate system shown in Figure 4 depicts the applicable geometry needed to derive the GPS/Doppler velocity-derived heading equation, namely,

$$\text{Heading} = \text{TAN}^{-1} \frac{\begin{vmatrix} V_N & V_E & - & V_N & V_D \\ H & E & & N & D \\ V_N & V_E & + & V_N & V_D \\ N & H & & D & E \end{vmatrix}}$$

where V_N, V_E = GPS derived velocities

V_N, V_D = Doppler derived velocities

With this GPS/Doppler Heading Reference, a non-magnetic, non-gyro-compass means of providing true heading has been found. It remains to be seen whether the accuracies ultimately possible with this system would justify using it as the primary heading reference for mission aircraft. However, it can be used to improve magnetic-and gyro-compasses via Kalman filtering to help overcome magnetic anomalies and to reduce gyro-compass errors through dynamic calibration/alignments. Also, where primary heading references may be a casualty, there now exists a "fall-back" heading reference.

CONCLUSIONS:

1. GPS-Doppler Navigator field testing in the New Jersey area must continue. The shape and range of the GPS position and velocity errors in this geographic area must be defined (as well as what has influenced these errors). Based on results of such testing, it may be that, from a world-wide deployment point of view under operational conditions, simple position update of a Doppler Navigator by GPS is of insufficient accuracy for attack and other high performance

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aircraft. In this event, some form of multi-state Kalman filtering would have to be employed.

2. The experimental exploration of the Hybrid Velocity Derivation of Heading and Attitude, which arose as a synergistic bonus under this program, must continue. Such experiments will help characterize the error budget that applies to and governs the accuracy of the heading, roll, and pitch that are so sensed.

3. Any GPS-Doppler Hybrid Kalman filter should address not only position and velocity improvement but derivation of heading and attitude as well. These derivations then may be used with the outputs of the independent aircraft heading and attitude sensors to improve overall heading and attitude information without paying for more expensive heading and attitude sensors.

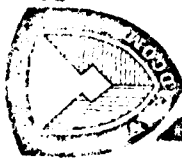
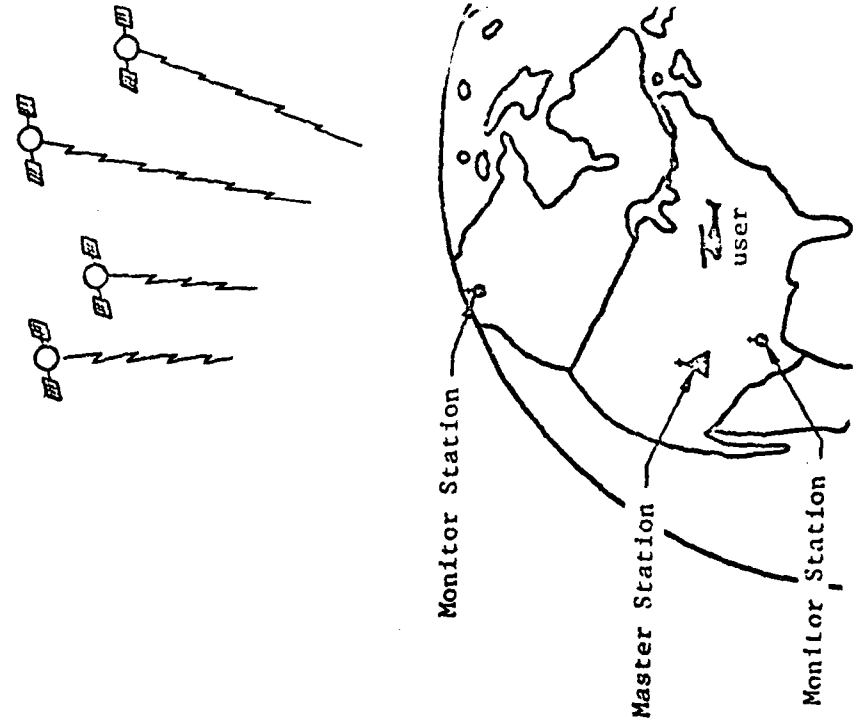
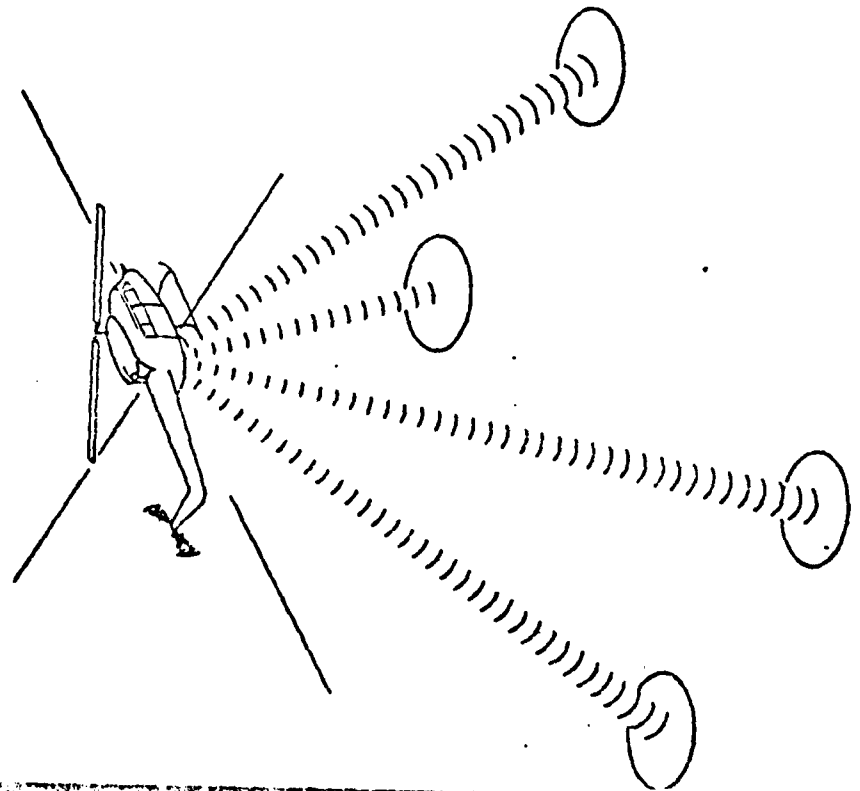
4. The principle of graceful degradation for high performance mission aircraft will be enhanced. Not only does this project offer "fall-back" capability in positioning under adverse conditions but, now, "fall-back" in heading and attitude as well.

³Patent Application, Docket #D-2071, Title: GPS/Doppler Velocity Derived Heading Reference System, Jack Gray

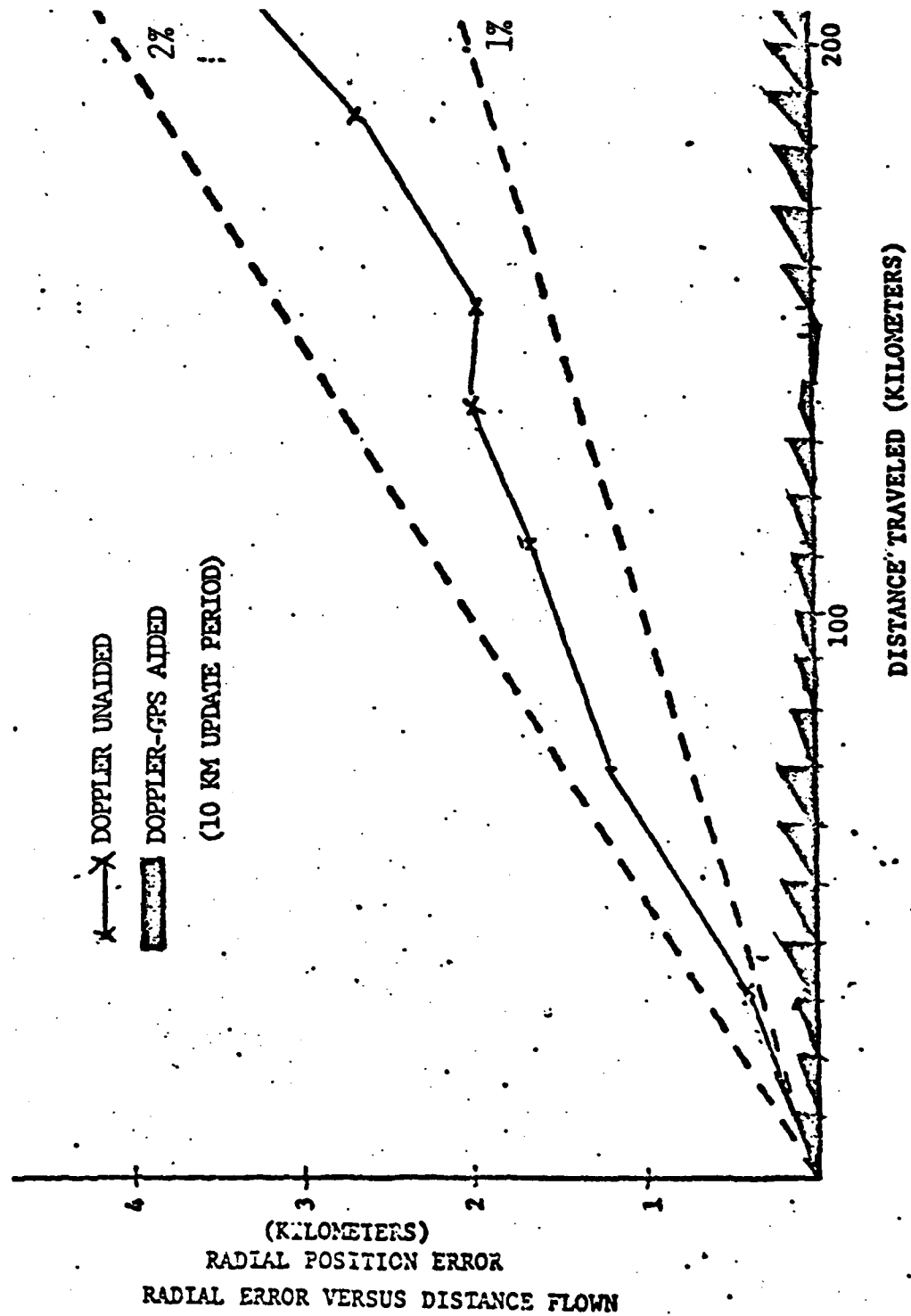
FIGURE 1 STAND ALONE NAVIGATION SYSTEMS

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GPS



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DOPPLER-GPS 10 KM UPDATE PERFORMANCE FIGURE 2



GPS DOPPLER HYBRID NAVIGATION SYSTEM

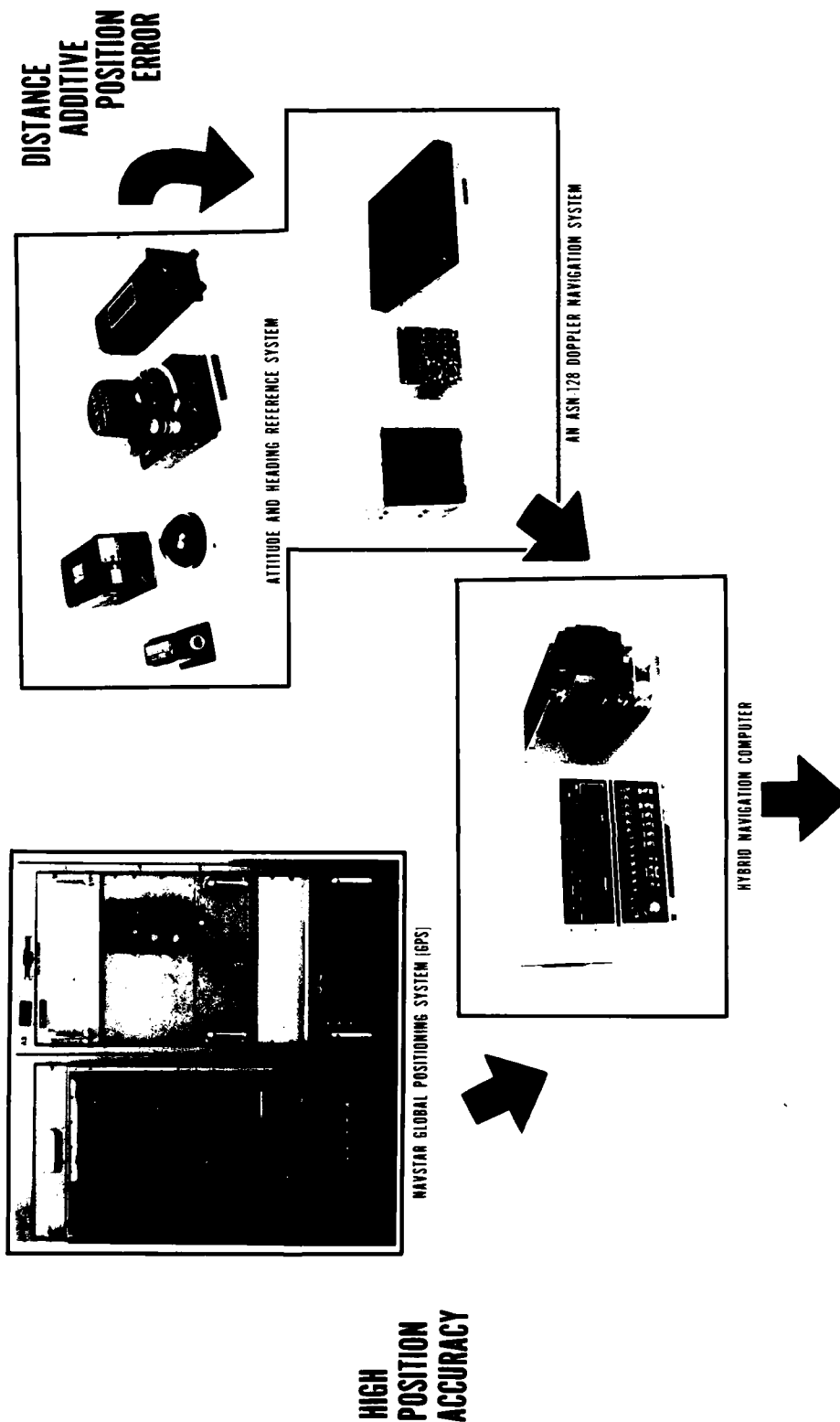
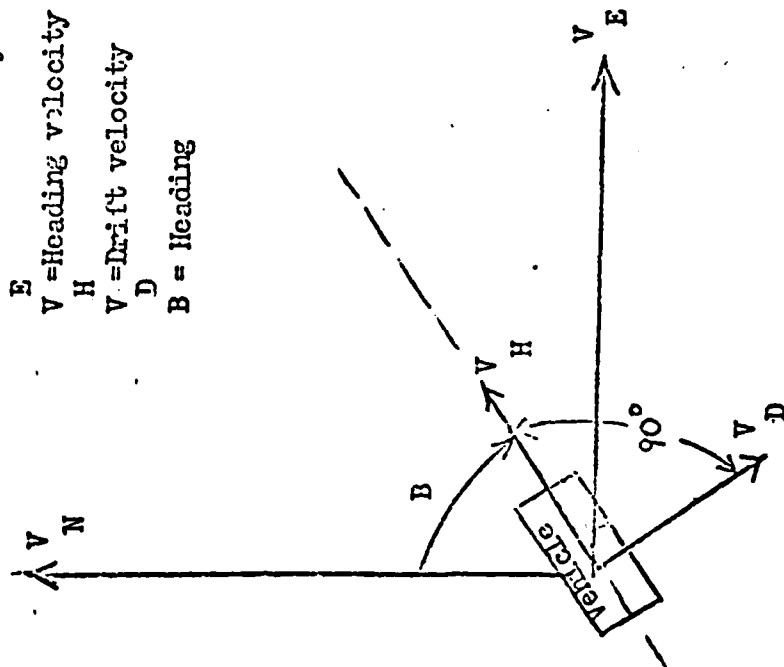


FIGURE 3

V_N = North velocity
 V_E = East velocity
 V_H = Heading velocity
 V_D = Drift velocity
 B = Heading



GPS/DOPPLER HEADING REFERENCE GEOMETRY FIGURE 4